A foreshock bubble driven by an IMF tangential discontinuity: 3D global hybrid simulation

Chih-Ping Wang[1], Xueyi Wang[2], Terry Z. Liu[3,4], Yu Lin[2]

1. Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, CA, USA
2. Physics Department, Auburn University, Auburn, AL, USA
3. Cooperative Programs for the Advancement of Earth System Science, University Corporation for Atmospheric Research, Boulder, CO, USA
4. Geophysical Institute, University of Alaska, Fairbanks, Fairbanks, AK, USA.

Corresponding authors: Chih-Ping Wang (cat@atmos.ucla.edu) and Xueyi Wang (wangxue@auburn.edu)

Key points

- A foreshock bubble (FB) formed upstream of a tangential discontinuity (TD) is simulated in 3D using the ANGIE3D hybrid code
- The FB is initiated by an increase of $T_{i,\perp}$ upstream contributed by the foreshock ions with large gyro radii moving across the TD
- The $T_{i,\perp}$ increase is due to the foreshock ion's $v_{\parallel}$ changing to $v_{\perp}$ as they experience the magnetic field direction change across the TD

Abstract. Foreshock bubbles (FBs) have been observed upstream of solar wind tangential discontinuities (TDs). A hypothesized mechanism is that foreshock ions with gyroradii larger than the TD thickness may move to upstream side of TDs and generate FBs. In this study, we present the very first three-dimensional global hybrid simulation of an FB driven by a TD. After the TD encounters the ion foreshock, plasma and magnetic field perturbations are generated upstream of the TD. These perturbations are characteristically consistent with the observed TD-driven FBs, confirming that TDs can form FBs. We further analyze the initial perpendicular temperature increase initiating the FB and compare the temperature structure with that from tracing test-particles in static TD electric and magnetic fields. The structure can be explained by the perpendicular velocity change of foreshock ions with large gyroradii as they encounter the magnetic field direction change across the TD, which supports the hypothesized mechanism.

1. Introduction

Ion foreshock transients are frequently generated in the foreshock (Zhang and Zong, 2020). Some of them are generated by the kinetic interaction of energetic foreshock ions with an interplanetary magnetic field (IMF) discontinuity, such as foreshock bubbles (FBs) (Liu et al., 2015; Omidi et al., 2010; Omidi et al., 2020; Turner et al., 2013;; Turner et al, 2020;) and hot flow anomalies (HFAs) (Chu et al., 2017; Lin, 1997; 2002; Liu et al., 2017; Lucek et al., 2004; Omidi and Sibeck, 2007b; Schwartz et al., 1985; Thomsen et al., 1986; Zhang et al., 2010; 2017;), while some are formed without an IMF discontinuity, such as diamagnetic cavities (Lin, 2003; Lin and Wang, 2005; Omidi, 2007a), foreshock cavitons (Blanco-Cano et al., 2011; Kajdič et al., 2013), and spontaneous hot flow anomalies (Omidi et al;, 2013; Zhang et al., 2013). Dynamic pressure perturbations associated with these foreshock transients can cause magnetopause distortion (Archer et al., 2014; 2015; Jacobsen et al., 2009; Lin et al., 2002;

Sibeck et al., 1999), subsequently causing enhancements in ultralow frequency (ULF) waves inside the magnetosphere (Hartinger et al.; Wang et al., 2017), aurora brightness (Fillingim et al., 2011; Wang B. et al., 2018a; 2018b), and ionospheric currents and ground magnetic field perturbations (Fillingim et al., 2011; Kataoka et al., 2002).

The FBs were first predicted by hybrid simulations (Omidi et al. 2010) to be generated by the interaction of foreshock ions with a rotational discontinuity (RD). The normal magnetic field of a RD allows foreshock ions to go through the RD to the upstream side. On the upstream side, they become more concentrated as they are deflected by the upstream VxB electric field. Consequently, their pitch angles increase as the magnetic field changes, resulting in increases in the temperature and thermal pressure (Archer et al., 2015). These heated foreshock ions upstream of the RD initiate the development of a hot and tenuous core that expands into the surrounding solar wind (foreshock bubbles). The core thus has lower density, higher temperature, and lower magnetic field strength than the surrounding solar wind. The supersonic sunward expanding of the core against the anti-sunward solar wind results in a fast magnetosonic shock (FB shock) at the upstream edge of the core. The edge thus has higher density and magnetic field strength than the surrounding solar wind. The solar wind flow slows down at the FB shock and is diverted around the FB.

The simulated RD-driven FBs were later confirmed by observations (Turner et al., 2013). In addition to be driven by an RD, Liu et al. (2015) observed FBs driven by tangential discontinuities (TDs). However, unlike an RD, a TD does not have a normal component that enables the crossing of the foreshock ions to the upstream side. Liu et al. (2015) hypothesized a mechanism that such TD crossing is possible for energetic foreshock ions whose gyroradii are larger than the TD thickness. As these ions gyrate across the TD and experience the change in the magnetic field directions, part of their parallel velocities is converted to perpendicular velocities, resulting in increases in the perpendicular (thermal) temperature and thermal pressure that develop into an FB. This hypothesized mechanism for TD-driven FBs has not been evaluated with global simulations.

In this paper, we present the first 3D global simulation of an FB driven by a TD using the AuburN Global hybrId CodE in 3-D (ANGIE3D) hybrid code (Lin et al., 2014). We show that perturbations with characteristics consistent with the observed FB reported in Liu et al. (2015) are generated upstream of the TD. We analyze the initial increase of the perpendicular temperature upstream of the TD and evaluate it with the mechanism hypothesized by Liu et al. (2015).

2. Simulation Setup

We use the ANGIE3D code to simulate the interaction of an IMF directional TD (i.e., with direction change only) with the foreshock ions. ANGIE3D has been used to simulate an FB driven by an RD (Wang et al., 2020). The simulation domain is $25 \geq X \geq -60$, $60 \geq Y \geq -35$, $35 \geq Z \geq -45$ R_E in the geocentric solar magnetospheric (GSM) coordinates. An inner boundary is assumed at the geocentric distance of $r \approx 3$ R_E. In the ionosphere, uniform Pederson conductance of 10 siemens and Hall conductance of 5 siemens are specified. The TD is specified as a planar IMF discontinuity with a half-width of 0.12 R_E and the normal direction of (–0.5, 0.86, 0). The TD propagates with a velocity of (–400, 0, 33.7) km/s. Unless otherwise noted, downstream (upstream) in this paper indicates the anti-sunward (sunward) side of the TD. At $t = 0$, the TD plane intersects the $Y = 0$ axis at $X = 185$ R_E. The downstream IMF direction is (3, 1.7, 0) nT and upstream IMF is (0, 0, 3.4) nT. Constant solar wind density of 5 cm^{-3} and isotropic solar wind ion temperature of 10 eV are used. The solar wind velocities are (–370.7, 16.8, 33.7) km/s downstream and (–400, 0, 0) km/s upstream. The average solar wind Alfvén Mach number is M_A = 11.8. These values are not unique and are just one of many choices within the typically observed ranges.

The values of the ion inertial length (d_i) and cell size are important to a hybrid simulation of foreshock transients as they can affect collisionless dissipation resulting in ion reflections and leakage from the bow shock (Omidi and Sibeck, 2007). For this large-scale simulation to be accomplished with the available computing resources and can still provide physical results, we choose the solar wind d_i to be 0.1 R_E (about 6 times larger than the realistic value), the cell dimensions to be $n_x \times n_y \times n_z$ = 425×440×440, and use nonuniform cell grids ($\Delta x = \Delta y = \Delta z$ = 0.12 and 0.15 R_E in the magnetosheath and the foreshock, respectively). These cell sizes are comparable to d_i. The bow shock and magnetopause form self-consistently. The bow shock nose is at X ~14 R_E and the magnetopause nose is at X ~10 R_E, similar to the realistic locations. As shown in Wang et al. (2020), these values of the cell sizes and d_i are adequate for quantitative evaluation of ion foreshock processes.

3. Simulation Results

3.1. FB Perturbations

Figure 1a shows the 2D profiles of B_z, ion density (N), ion parallel temperature ($T_{i,||}$), and ion anti-sunward flow speed ($-V_x$) on the X-Y plane at Z = –5 R_E at t = 42. 8 (left panels) and 51.2 min (right panels) (note that the X and Y ranges for these two times are different). The white or black dotted lines indicate the TD plane. The black solid lines are along the TD normal. The 1D cross-TD profiles along the black solid lines are shown in Figure 1b as a function of dS (dS is the distance to the TD plane and is defined to be positive (negative) on the downstream (upstream) side). The 2D profiles on the TD normal plane along the black solid lines are shown in Figure 1c as a function of X(Y) and Z.

As shown in Figure 1a, at t = 42. 8 min, the TD in the X-Y plane at Z = –5 R_E encounters the bow shock on the dawn side at Y ~ –8 R_E, but it has not come into contact with the ion foreshock (the magenta dashed curve in the $T_{i,||}$ plot marks the ion foreshock boundary). The cross-TD profile shows a small temperature peak and small |B| dip within the TD layer (indicated by the yellow shaded region in Figure 1b), which is the TD's steady state force-balanced structure. The ion foreshock, as indicated by the region of high temperature (indicated by "foreshock" in the $T_{i,||}$ plots), is mainly on the dusk side (Figure 1a) and centered around the equatorial plane (Figure 1b). Within the foreshock, there are localized (~ 2-3 R_E) perturbations in plasma and magnetic field associated with foreshock ultralow frequency (ULF) waves (periods of ~2 min) (indicated by "ULF" in the density and |B| plots). The ULF waves also interact with the bow shock, which repeatedly causes distortion of the quasi-parallel bow shock, including localized outward extension (indicated by "outward bow shock" in the density plot).

At t = 51.2 min, as shown in Figures 1a-1c, the TD plane has encountered the foreshock ions and large plasma and magnetic field perturbations are generated around the TD. Importantly, the perturbations in some places are seen to be well within the upstream side. They consist of a core with lower density, higher temperature (both parallel and perpendicular temperatures), and lower magnetic field strength than the values in the solar wind (indicated by "core" in Figures 1a-1c). A round edge with relatively higher density and higher magnetic field strength resulting from the expansion of the core is formed on the upstream side of the core (indicated by "edge" in Figures 1a-1c). In addition, the expansion also results in divergence of the flow velocities with a decrease in the $–V_{i,x}$ speed and increases in the V_y and V_z speeds. These plasma and magnetic field perturbations upstream of the TD resulting from the encounter of the TD with the foreshock ions are characteristically consistent with the FBs formed upstream of an RD. The cross-TD profiles shown in Figure 1b are also similar to the observed FBs upstream of TDs reported by Liu et al. (2015). Thus, this simulation shows that FBs can be driven by TDs.

As shown in Figures 1a and 1b, at t = 51.2 min, the FB extends outward for < 5 R_E from the bow shock (Figure 1a). This spatial span is considerably smaller than the span of the ion foreshock in contact with the TD plane, which extends more than 10 R_E outward from the bow shock. This is different from the FBs driven by RDs shown in the simulations (Omidi et al., 2020). The RD's normal component enables the foreshock ions to cross the entire RD so that the ion foreshock and the resulting FB on the two sides of the RD have similar spatial spans. As for the TD case, because magnetic field lines are tangential to the TD normal, it is the same group of foreshock ions along this spatial span. After some of these foreshock ions cross the TD near the bow shock to form the FB, they can hardly come back downstream, move along the field lines further away from the bow shock, and cross the TD again. Additionally, although the foreshock region is spatially symmetric in the Z direction about the equator, the FB core region is preferentially in the Z < 0 region (Figure 1c). The reason is discussed in section 3.3.

While the FB is formed upstream of the TD, perturbations are also seen downstream. Distinguishably different from the FB's well-structured high-N and high-B edge, the localized high N and high B regions seen on the downstream side within |Z| < ~ 10 R_E are associated ULF waves or the localized outward extension of the bow shock. They are not driven by the TD since they have existed there long before the arrival of the TD.

3.2. Temperature Increase Upstream of the TD

The well-developed FB shown in Figure 1 is initiated by an increase of perpendicular temperature ($T_{i,\perp}$) upstream of the TD soon after the TD encounters the ion foreshock. To show this initial temperature increase, we plot in Figure 2 the temperatures across the TD at t = 43.4 min when the TD plane first encounters the ion foreshock boundary, and one minute later at t = 44.3 min. Figures 2a and 2c show the $T_{i,\parallel}$ and $T_{i,\perp}$ distributions, respectively, in the X-Y plane at Z = –6 R_E at t = 43.4 (top) and 44.3 min (bottom), and Figures 2b and 2d show the cross-TD profiles for $T_{i,\parallel}$ and $T_{i,\perp}$, respectively, along the black lines indicated in Figures 2a and 2c. The black lines at the two times are different but both are about 2 R_E from the bow shock. Figures 2d and 2e show the spatial distributions of $T_{i,\parallel}$ and $T_{i,\perp}$, respectively, on four different planes parallel to the TD plane (two upstream, and two downstream) at t = 43.4 (top) and 44.3 min (bottom). In the ion foreshock, $T_{i,\parallel}$ is substantially higher than $T_{i,\perp}$, (note the different color bar ranges for the $T_{i,\parallel}$ and $T_{i,\perp}$color plots), and both temperatures are the highest just outside the bow shock.

Comparing the temperature profiles between t = 43.4 and 44.3 min clearly shows the temperature increase upstream resulting from the encounter of the foreshock ions with the TD. The initial increase is seen in both $T_{i,\parallel}$ and $T_{i,\perp}$ within the TD layer, and in $T_{i,\perp}$ upstream of the TD layer, which clearly indicate that some of the foreshock ions go through the TD to the upstream side. Compared to the temperatures of the foreshock ions immediately outside the TD layer, the ions penetrating into the TD result in relatively lower $T_{i,\parallel}$ but higher $T_{i,\perp}$. As explained later, the opposite $T_{i,\perp}$ and $T_{i,\parallel}$ changes are associated with changes in these ions' pitch angles.

Figures 2e and 2f for t = 44.3 min show that the temperatures within the TD layer (dS = +0.1 and –0.1) and further upstream (dS = –0.7) have spatial distributions quite different from that in the foreshock region (dS = +0.7). In foreshock, the high $T_{i,\parallel}$ region extends outward from the bow shock around the equator, while the high $T_{i,\perp}$ region is only seen quite close to the bow shock. From the foreshock to the TD layer, the high $T_{i,\parallel}$ region shifts southward to Z < 0 region, and a high $T_{i,\perp}$ region appears in the same region. This high $T_{i,\perp}$ region is still seen from within the TD layer to farther upstream, while the high $T_{i,\parallel}$ region diminishes. This initial $T_{i,\perp}$ enhancement in the Z < 0 region explains why the resulting FB core shown in Figure 1c is preferentially at Z < 0.

3.3. Test Particle Perspective

To understand the initial $T_{i,\perp}$ enhancement and its spatial distribution upstream of the TD shown in Figure 2 for t = 44.3 min from a particle's perspective, we trace a proton's motion with the equation of motion and investigate the changes in the proton's parallel velocity ($v_\parallel$) and perpendicular velocity ($v_\perp$) as it encounters a TD. For this tracing, the TD (thickness and moving velocities) and the associated magnetic field and convection electric field are assumed to be time-independent and their values are the same as those described in section 2. To evaluate protons of different gyroradii, we conduct the particle tracing for three 5 keV protons ($|v|$ = 979 km/s) at three different pitch angles, 10°, 40°, and 60°, with respect to the downstream field. These three protons are good representative of the simulated foreshock ion population. These protons are traced for 60 s and the results are shown in Figure 3. To better show the particle's location relative to the TD plane, we rotate the X-Y-Z GSM coordinates about the Z axis to X'-Y'-Z' coordinates so that Z' = Z_{GSM}, Y' is the direction of the TD normal, and X' is on the TD plane. As shown in Figures 3a, at t = 0, the TD plane is set at Y' = –1.7 R_E (the vertical dotted line) and the test particles are placed 0.6 R_E downstream at (13, –1, 0) R_E (the black dots). At t = 60 s, TD propagates to Y' = 0.28 R_E (the vertical line). As shown in Figure 3h, the downstream magnetic field is (3.4, 0, 0) nT, and upstream magnetic field is (0, 0, –3.4 nT). The corresponding gyroradii are 0.08, 0.3, and 0.4 R_E for the protons of 10^o, 40^o, and 60^o pitch angle, respectively. The trajectories of the three protons from t = 0-60 s in the X'-Y' and X'-Z' planes are shown in Figures 3a and 3b, respectively. Note that the use of time-independent undisturbed field configurations in this tracing is appropriate since our objective is to understand the initial temperature increase before the development of the FB so that the fields have not been disturbed.

Figure 3c shows each particle's locations relative to the TD plane (Y'-Y'_{TD}), Figures 3d-3e show the magnetic field $B_{x'}$ and $B_{z'}$, respectively, experienced by each particle, and Figures 3f and 3g show each particle's $v_{||}$ and $v_{\perp}$, respectively, as a function of time. Figure 3h shows $B_{x'}$ and $B_{z'}$ and Figures 3i and 3h show $v_{||}$ and $v_{\perp}$ from t = 0-60 s, respectively, as a function of Y'-Y'_{TD}. As indicated in Figure 3h, we select four regions relative to the TD plane: R1 is the foreshock region; R2 is within the TD layer downstream of the TD; R3 is within the TD layer upstream of the TD; and R4 is upstream of the TD layer. These four regions correspond to the four planes shown in Figures 2e-2f. Figure 3k shows each particle's locations, $v_{||}$, and $v_{\perp}$ from t = 0-60 s as a function of X' and Z' in R1-R4.

Figures 3c and 3i show that the proton of 10^o pitch angle remains in the foreshock (R1) during the 60 s period. Thus, it does not experience changes in magnetic fields and its $v_{||}$ also remain unchanged. Its $v_{\perp}$ fluctuates in a period of ~19 s associated with gyrating in the convection electric field, but the range of the $v_{\perp}$ fluctuation and the gyro-averaged $v_{\perp}$ does not change. For the proton of 40^o pitch angle, it can gyrate into the TD layer (R2 and R3) and experience a change in the magnetic field directions. As a result, when it was within the TD layer, its $v_{||}$ decreases while the gyro-averaged $v_{\perp}$ increases, as shown in Figures 3f-3g and 3i-3j (note that the gyro-averaged |v| is conserved). Similarly, the proton of 60^o pitch angle can go further upstream to R4, its $v_{||}$ decrease and become negative while the gyro-averaged $v_{\perp}$ increases. That the protons of 40^{o} and 60^{o} pitch angles can move through the TD because of their large gyroradii relative to the TD thickness and that their $v_{||}$ is converted to $v_{\perp}$ as they experience the changes in magnetic field directions are the mechanism hypothesized by Liu et al. (2015). Since protons of larger gyroradii can go further upstream of the TD, they result in the cross-TD profiles of decreasing $v_{||}$ but increasing $v_{\perp}$ with increasing upstream distances from the TD shown in Figures 3i-3j, which explains the opposite $T_{i,\perp}$ and $T_{i,||}$ changes from the foreshock to the TD shown in Figure 2.

As these test ions gyrate in R1 to R4, they also move along the different $B_{x'}$ and $B_{z'}$ in these regions shown in Figure 3h, thus their trajectories become separated, as shown in Figures 3a and 3b. Their movement to different X' and Z' locations and their different $v_{||}$ and $v_{\perp}$ values in R1 to R4 can explain the different $T_{i,\perp}$ and $T_{i,||}$ spatial distributions between the foreshock and the upstream region shown in Figures 2e-2f. Each particle's locations from t = 0-60 s and its $v_{||}$ and $v_{\perp}$ are plotted in Figure 3k as a function of X' and Z' for regions R1 to R4 for comparing with the spatial distributions on the four dS planes shown in Figures 2e-2f. When in region R1, the test protons move toward positive X' (outward from the bow shock) along the positive B_{x}. They move both outward and southward in the positive $B_{x'}$ and negative $B_{z'}$ fields when in R2 and R3, and move southward in R4 following the negative $B_{z'}$ due to the newly projected parallel speed. In R1, the proton of 10^{o} pitch angle moves the farthest outward from the bow shock around Z' ~0 and it has largest $v_{||}$ among the three ions, this accounts for the foreshock $T_{i,||}$ spatial distribution shown in the dS = +0.7 plot of Figure 2e with the high $T_{i,||}$ region extending outward around the equator. Comparing with R1, only the protons of 40^{o} and 60^{o} pitch angles appear in

R2 and R3, thus their locations in the Z' < 0 region explain the southward shifting of the high $T_{i,||}$ region from the foreshock to the TD layer shown in Figure 2e. In addition, their $v_\perp$ values are higher in R2 and R3 than in R1, thus explaining the $T_{i,\perp}$ enhancement within the TD layer appearing southward of the equator shown in Figure 2f. Only the proton of 60^o pitch angle can go to R4. Thus its $v_\perp$ and $|v_{||}|$ changes from R2 to R4 explains why the high $T_{i,\perp}$ region shown in Figure 2f is seen to extend upstream to the S = –0.7 plane while the high $T_{i,||}$ region shown in Figures 2e does not extend as far. The above test-particle prospective supports the mechanism by Liu et al. (2015).

4. Summary and Discussion

We present the first 3D global hybrid simulation of an FB driven by a TD, and investigate its spatial structure and the formation mechanism. The FB is formed on the upstream side of the TD. The FB consists of a core of low density, high parallel and perpendicular temperatures, and low magnetic field strength and an edge of high density and high magnetic field strength upstream of the core. The solar wind flow slows and is diverted around the FB. These characteristics are consistent with observed TD-driven FBs. Compared with the locations of the foreshock ions encountering the TD, the locations of the resulting FB are shifted toward the direction of the upstream magnetic field, in our case, shifted southward in the negative IMF B_z upstream field. Soon after the TD encounters the foreshock ions, there is an enhancement in the perpendicular temperature that initiates the FB. By comparing with the results of test-particle tracing of protons of different gyroradii, we show that the initial enhancement is contributed by the crossing of foreshock ions with gyroradii larger than the TD thickness, and the increase of their perpendicular velocities is converted from their parallel velocities. This simulation thus supports the mechanism for the TD-driven FBs hypothesized by Liu et al. (2015).

The above mechanism requires foreshock ions with gyroradii larger than the TD thickness. Thus, it is expected that a thinner TD and/or more energetic foreshock ions with larger perpendicular velocities are more favorable for the mechanism. A kinetic formation model based on particle-in-cell simulations (An et al., 2020) and MMS observations (Liu et al., 2020a) suggests that the discontinuity configuration determines how foreshock ions become demagnetized, which generates a Hall current that shapes the magnetic field profile of a foreshock transient.

Observations (Liu et al., 2016) indicate that under the same solar wind conditions, a thin TD forms an FB and a thick TD forms an HFA. Both FBs and HFAs can result in significant geoeffects and particle acceleration, and their impact may extend to the midtail (Liu et al., 2020b; Wang et al., 2018; Wang et al., 2020). Comparing with HFAs, FBs are larger in size so that their impact can be more global (Acer et al., 2015). The FB shock on its upstream side can accelerate solar wind particles through shock drift acceleration (Liu et al., 2016). Without a downstream boundary, particles experience Fermi acceleration more freely between the FB shock and bow shock (Liu et al., 2017, 2018). Therefore, FBs can also contribute more to particle acceleration at the bow shock or other shock systems than HFAs. This study confirms that TDs can also form FBs, implying that FBs and their stronger effects can occur more frequently than previously thought.

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Caption

Figure 1. (a) The X-Y profiles at Z = –5 R_E for B_z, N, $T_{i,||}$, and $-V_x$ at t = 42.8 (left panels) and 51.2 min (right panels). The dotted lines indicate the TD plane. The black solid lines are along the TD normal. The magenta dashed curve in the $T_{i,||}$ plot marks the ion foreshock boundary. (b) The cross-TD profiles along the black solid line indicated in (a) as a function of the distance to the TD plane (dS is positive (negative) on the downstream (upstream) side of the TD) for magnetic field components, density, ion temperatures, and velocity components. The yellow shaded region indicates the TD layer. (c) The 2-D profiles of B_z, N, $T_{i,||}$, $-V_x$, $|B|$, $T_{i,\perp}$ and V_y on the TD normal plan along the black line indicated in (a). The vertical dotted lines indicate the TD plane.

Figure 2. Ion temperature distributions in the X-Y plane at Z = –6 R_E for (a) $T_{i,||}$ and (c) $T_{i,\perp}$ at t = 43.4 (top) and t = 44.3 min (bottom). Comparison of the cross-TD profiles as a function of dS between t = 43.4 (blue line) and 44.3 (red line) min for (b) $T_{i,||}$ and (d) $T_{i,\perp}$ along the black solid lines indicated in (a) and (c). The 2-D temperature profiles on four different planes parallel to the TD plane with dS indicated on the top for (e) $T_{i,||}$ and (f) $T_{i,\perp}$ of at t = 43.4 (top) and 44.3 min (bottom). In order to better show the temperatures outside the bow shock, the region inside the bow shock is plotted in white in (a), (c) (e) and (f).

Figure 3. Test particle tracing for three 5 keV protons in three different pitch angles. Particle trajectories from t = 0-60 s on (a) X'-Y' and (b) X'-Z' planes for the three particles (indicated by different colors with their pitch angle values shown in (a)). The vertical dotted (solid) line in (a) indicates the TD at t = 0 (60) s. The black dot in (a) and (b) indicate the particle locations at t = 0. (c) The particle's Y' locations relative to the TD plane ($Y'–Y'_{TD}$), (d) B_x' and (e) B_z' experienced by each particle and the particle's (f) $v_{||}$ and (g) $v_{\perp}$ as a function of time. (h) B_x' and B_z', the test particle's (i) $v_{||}$ and (j) $v_{\perp}$ from t = 0-60 s as a function of $Y'–Y'_{TD}$. The two vertical dotted lines indicate the TD thickness. (k) Each test particle's Z' locations (top), $v_{||}$ (middle), and $v_{\perp}$ (bottom) as a function of X' in the four different regions (R1-R4) indicated in (h).